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AND HIGHLY INSULATING WINDOW SYSTEMS

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ABSTRACT

Data on window heat-transfer properties (U-value and shading coefficient [SC]) are usually presented only for a few window designs at specific environmental conditions. With the introduction of many new window glazing configurations (using low-emissivity coatings and gas fills) and the interest in their annual energy performance, it is important to understand the effects of window design parameters and environmental conditions on U and SC. This paper discusses the effects of outdoor temperature, wind speed, insolation, surface emittance, and gap width on the thermal performance of both conventional and highly insulating windows. Some of these data have been incorporated into the fenestration chapter of the ASHRAE Handbook— 1985 Fundamentals.

The heat-transfer properties of multiglazed insulating window designs are also presented. These window systems include those having (1) one or more low-emittance coatings, (2) low-conductivity gas-fill or evacuated cavities, (3) a layer of transparent silica aerogel, a highly insulating microporous material, or (4) combinations of the above. Using the detailed building energy analysis program, DOE 2.1B, we show that these systems, which all maintain high solar transmittance, can add more useful thermal energy to a space than they lose, even in a northern climate. Thus, in terms of seasonal energy flows, these fenestration systems out-perform insulated walls or roofs.

INTRODUCTION

Until recently, investigation of heat transfer through windows has been limited to study of only a few window designs at winter and summer peak conditions. However, growing interest in reducing energy flows through fenestration has brought about both a wide variety of energy-conserving window designs and the need to analyze window heat transfer under diverse environmental conditions. It is therefore important to reexamine the standard procedures used to analyze window heat transfer and the format in which these data are presented.

We begin by parametrically analyzing environmental and window-design factors that influence window heat transfer. The numerical effects of these factors on a window's U-value and shading coefficient are presented and discussed; important effects are singled out and noted. We discuss results for a range of existing and emerging generic glazing systems. Those interested in determining U and SC for specific window products can utilize a recently released computer model, WINDOW (Arasteh 1985).

We also present thermal-performance data for several highly insulating window designs. These "superwindows" are based on combinations of several state-of-the-art fenestration technologies and offer the prospect of drastically reducing window heat-transfer rates while still maintaining high solar transmittance. The potential for these windows to provide positive seasonal energy flows has been analyzed and is briefly summarized here.

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NOMENCLATURE

T_o: outside temperature
T_i: inside temperature
T_g: glazing temperature
I: solar insolation
v: wind speed
e: surface hemispherical infrared emittance
ASHRAE design conditions (1985 Fundamentals):
  winter: T_o=0 F (-18°C); T_i=70 F (21°C); v=15 mph (6.7 m/s); I=0
  summer: T_o=89 F (32°C; T_i=75 F (24°C); v=7.5 mph (3.3 m/s); I=248.3 Btu/h/ft^2 (783 W/m^2)
h_o: exterior film convection coefficient
h_i: interior film convection coefficient
h_g: gap space convection coefficient
t: transmittance for a single glazing layer
r: reflectance for a single glazing layer
a: absorptance for a single glazing layer
$t^\prime$: transmittance for a single glazing layer in a system of multiple glazing layers
$a^\prime$: absorptance for a single glazing layer in a system of multiple glazing layers

Modeling the Thermal Performance of Windows

     To determine the thermal transfer properties of a window (U, SC) we have developed an analytical computer program, WINDOW (Arasteh 1985, Rubin 1982) which models heat transfer through the glazed area of a window only. WINDOW's capabilities include the ability to vary the following parameters:

   -- number of glazing layers

   -- visible and solar optical properties

   -- thermal infrared properties

   -- gap widths

   -- gap-space gas composition

   -- environmental conditions (outdoor and sky temperatures, incident solar radiation, wind speed)

We report results in terms of conventionally defined heat-transfer terms, U-value and shading coefficient (SC). However, we believe that in the future other more specific terms for overall window heat transfer and solar heat gain might be developed.

WINDOW'S results for specific window systems compare favorably with experimental data (Rubin 1982) and results from a similar program (Ferguson and Wright 1984; Barakat 1985).

ENVIRONMENTAL AND WINDOW-DESIGN FACTORS AFFECTING THE U-VALUES AND SHADING COEFFICIENTS OF LOW-E WINDOWS

Environmental Conditions

     In this section we assess the influences of environmental parameters (T_o,I,v) on U-values and shading coefficients (SC) of conventional and highly insulating windows. Figure 1 presents winter and summer U-values as a function of outdoor temperature, wind speed, and incident solar radiation levels for several window configurations. Unless otherwise noted, summer U-values are calculated at ASHRAE conditions. From this graph we can summarize the effects of environmental parameters on window U-values as follows:

     Wind Speed: Wind speed (V) and direction affect the resistance value of the outdoor film coefficient (ho). Where this film resistance is a noticeable component of the window's total resistance (i.e., single glazing, and double glazing to a lesser extent), the effect of wind speed on a window's U-value should be carefully considered. Wind effects are less noticeable with highly insulating window systems (i.e., double glazing with low-e coatings, triple glazing, etc.).

Outdoor Temperatures: Changing the temperature difference between a pane and the surrounding air layer will alter convective heat transfer. As more glazing layers are added, the temperature difference between the layer and the surrounding air is smaller and the change in U-value with T_o is reduced. The U-value of single glazing, especially with a low-e coating (where convection/conduction dominate) is particularly sensitive to temperature differentials.

Incident Solar Radiation: Incident solar radiation affects the temperature of the glazing layers as a function of their absorptances but does not noticeably alter the exterior-film coefficient, which is predominantly a function of wind speed. However, h_i and h_g, as well as radiation exchange between nonexterior surfaces, will rise or fall with increasing or decreasing temperature differences between surfaces. The effect of solar radiation on U-values can be significant and varies considerably with T_o, glazing type, and most importantly, glass absorptance. Where solar radiation's influence is important, transmittance and absorptance as a function of angle of incidence must also be considered.

Figure 2 shows that a shading coefficient of a window with small absorptance will vary inconsequentially with variations in T_o and v. Slight variations are seen with 1/4-in heat-absorbing glass and to a lesser degree with heat-absorbing double glazing (clear inner light). These shading coefficients are based on $I = 248.3$ Btu/h/ft^2 (783 W/m^2). Lowering I (with the exception of single heat-absorbing glazing) will not alter SC. With single heat-absorbing glazing, at temperatures above 50-65F (10-18°C), decreasing I will reduce $T_g - T_i$, thereby lowering SC by 1%-3%. At lower temperatures, decreasing I will minimally increase SC because the temperature differential will rise. The exact crossover temperature will depend on wind speed.

Window Design Parameters: U-values

U and SC are also a function of window parameters. For this part of our analysis, we will assume ASHRAE winter design conditions. We discuss the most significant winter design parameters affecting window U-values: gap width, gap gas fill, and the number and placement of low-e coatings.

Gap width: Heat transfer through air-filled gaps is dominated, at small gap widths (<1/4 in or 6 mm), by conduction through the air. (Note that the thermal conductivity of air is approximately 1/40 that of glass.) As gap width increases, conduction through the air is linearly reduced in proportion to the thermal conductivity of air. However, as the gap width and/or temperature gradient increases beyond certain points, heat transfer by convection between the panes becomes more significant. Increasing the gap width beyond 1/2-3/4 in (13-16 mm) does not lower, and may even increase, the gap heat-transfer coefficient. Adding more gaps reduces overall heat transfer, although the law of diminishing returns soon takes effect.

Gas Fills: By replacing the air between glazing panes with a gas having a lower conductivity, we reduce the rate of heat transfer between glazing panes. The ideal gas for our purposes would be one having a very low conductivity and a high kinematic viscosity. However, in general, as conductivity decreases, kinematic viscosity also decreases, and therefore trade-offs must be made. Other options not yet thoroughly investigated include using mixtures of gases.

At a gap width of 1/4 in, replacing air with argon, dichlorodifluoromethane (CCl_2F_2), krypton, or sulfur-dioxide reduces h_g by 15% to 35%. The promise of gas fills is that h_g values lower than the best achievable with air at large gap widths can be realized with gap widths half the size, thereby making double- or triple-glazed windows less bulky and more economical. This improvement is achieved without any loss in solar transmittance. The relative improvements are further magnified in a window with reduced radiative transfer, e.g., a window with a low-e coating. Figure 3 presents U-value data for low-e double- and triple-glazed gas-filled windows under winter conditions as a function of gap width. Since the kinematic viscosity of Kr is much lower than that of either air or Ar, its h_g values are relatively constant for the gap widths considered here. In addition, because the thermal conductivity of Kr is also much lower, the relatively constant h_g is much lower than any achievable with air or Ar. While Kr's cost may be high, its thermal performance is presented here as an example of the "optimum" potential with gas-filled windows. The substitution of low-conductance gases in windows without low-e coatings will reduce conductive/convective heat transfer by the same absolute amount; however, this amount will be a proportionally smaller fraction of total window heat transfer.

Other characteristics besides heat transfer must be considered in selecting appropriate gases for window cavities. The gas must not be toxic, must not chemically attack window elements such as coatings, and must not diffuse through sealants, be degraded by exposure to solar or ultraviolet radiation, or condense at low temperatures. Finally, the gas must be available at reasonable cost. As a result of these criteria, Ar and SF_6 or a mixture of these two appear to be the most commercially viable. Many European window companies manufacture gas-filled windows in significant quantities, and U.S. manufacturers are beginning to offer gas-filled products. The single greatest uncertainty at present is proper specification of desiccants and sealants. However, European experience suggests that there are technically viable, cost-effective solutions.

Low-Emittance Coatings: Figure 4 shows U-values of double-glazed windows as a function of the emittance of the #2 (or #3) surface under typical winter conditions. We notice a continual decrease in U-value with decreasing emittance. Under winter (nighttime) conditions, a low-e window's U-value will be identical if the coating is moved to the surface across an interior air gap (i.e., for double and triple glazings, the U-value will be the same for coatings placed on the #2 or #3 surface; for triple glazing, the U-value will be the same if the coating is on the #4 or #5 surfaces). Figure 4 also shows the U-value of a double-glazed window with a low-e coating (e = 0.15) on the #3 surface as a function of the emittance on the #2 surface. Adding a second low-e coating to the glazing surface facing the same air gap as the first low-e coating provides only a small additional in radiative heat transfer, if the first coating has a relatively low emittance, e= 0.15. However, if the emittance of the surface is higher, for example e= 0.35, then a second coating will have a greater effect.

Currently, we can group low-e coatings into two categories. The first high-transmittance low-e coatings developed commercially in the U.S. were multilayer vacuum-deposited "soft coats" and were not highly resistant to abrasion or corrosion. These coatings have very low emittances (0.05 -0.15) but must be placed in a sealed double-glazed unit (i.e., on the #2 or #3 surface of double glazing). However, a new group of low-e coatings, "hard coats," applied pyrolytically in the float glass production process, are now emerging as a commercially viable technology. These coatings, while generally having somewhat higher emittances than soft coats (0.2 - 0.4), are sufficiently durable to be placed on exposed interior surfaces, nonsealed double glazing, storm windows and in some cases, on outer surfaces. (At least one manufacturer offers a pyrolytic hard coat with e ~ .15). The use of hard coats thus expands window-design possibilities and can provide U-values close to those possible with soft coats for an equivalent window design. For example, a double-glazed window with hard coats (e = .35) on the #2 and #4 surfaces under standard ASHRAE winter conditions will have a U-value of 0.35 $Btu/h/ft^2F$ (1.97 $W/m^{2o}C$).

Window Parameters: Shading Coefficients

Shading coefficients are primarily a function of the glazing's transmittance (t), reflectance (r), and absorptance (a) properties. Recent extensive measurements of the optical properties of soda lime glass (Rubin 1985) propose the use of new solar optical property values (t=.84, r=.07, a=.09) for reference soda lime DSA glass. These changes result in SCs slightly different than those currently prescribed in ASHRAE Fundamentals (i.e., for double glazing, SC=0.89 instead of 0.88 [ASHRAE 1985]). We use these new values in our work.

Glazings with low-e coatings normally have higher absorptance and lower transmittance than similar uncoated glazings. In buildings where the heating load dominates and winter solar gains are usually beneficial, the glazing layer with the low-e coating (highest absorptance) should be placed on the #3 surface in double glazing and on the #5 surface on triple glazing. This allows a greater fraction of solar energy absorbed by the glazing elements to flow inwards. Conversely, where solar gains must be controlled to reduce cooling loads, the low-e coating should be placed on the #2 surface of double or triple glazing.

Figures 5 and 6 present SC as a function of transmittance and absorptance for double glazing with varying low-e coatings on the #3 surface (Figure 5) and on the #2 surface (Figure 6). Transmittance and absorptance are given for the coated glass or plastic substrate only (substrate plus coating) while the SC applies to the entire glazing system. The remaining light of glass is assumed to be clear and 1/8 in (3 mm) thick. These and similar curves for triple glazing are presented in ASHRAE Fundamentals (ASHRAE 1985). Linear interpolation between the values presented can be used to determine the shading coefficient for specific emittances. Shading coefficients for windows without low-e coatings remain essentially similar to those presented in ASHRAE Fundamentals (with the exception of the influence of the new

solar optical properties values proposed by Rubin [1985]) (ASHRAE 1985).

WINDOW DESIGNS FOR R3 – R10 WINDOWS

The low-cost production of low-e-coated substrates has set the stage for a new generation of highly insulating (R3 – R10) windows that effectively suppress both radiative and conductive/convective heat transfer. This can be achieved through a variety of technical approaches using (1) proven available technologies in conventional window designs; (2) existing technologies in new designs; and (3) new insulating materials. Though the practicality and cost effectiveness of these designs are not well understood, we can with confidence predict the heat-transfer rates of many alternative designs.

Using Commercially Available Technologies

Low-e coatings are now a proven technology to reduce heat transfer through windows. In order to reduce conductive and convective heat transfer through windows with low-e coatings, we can:

-- use multiple glazing layers (three or more where the interior layers are thin-film plastics, the exterior is glass)

-- use low-conductivity gas or gas-mixture fills

-- use combinations of multiple glazing layers with low-conductivity gas fills.

The U-values of various windows using these components are shown in Table 1. These window systems are described below. For the purpose of these illustrative examples we assume soft coats have e = 0.15 and hard coats have e = 0.35.

-- G-G: Reference double glazing (e = 0.84)

-- GE_h-E_hG: Double glazing with e=.35 coatings (hard coat) on surfaces #2 and #3

-- G-E_sG: Double glazing with a low-e (e=.15) coating on surface #3

-- G-$E_s$$GE_h$: Double glazing with a low-e (.15) coating on surface #3 and a low-e (.35) coating on surface #4

-- G-E_sG-G: Triple glazing with a low-e (.15) coating on surface #3

-- G-E_sG-E_sG: Same as G-E_sG-G with an e=.15 coating also on the #5 surface

-- G-E_sG-E_sG-G: Quadruple glazing with low-e (0.15) coatings on surfaces #3 and #5

Where there are inner glazing layers with or without low-e coatings, a thin plastic film (usually polyester) is often used instead of glass to reduce weight and thickness. Using a thin film without a low-e coating increases solar transmittance and increases the U-value slightly compared to similar cases using glass, because the plastics are slightly transparent to infrared radiation. However, in the case where low-e coatings would be applied to the plastic films, thereby reducing their infrared transmittance, the U-values would be very close to those presented in Table 1. Table 1 presents U-values at standard ASHRAE winter conditions for the above window systems assuming 1/4-in and 1/2-in (6.3-mm and 13-mm) gaps filled with air, argon, or krypton.

We notice that:

1. Once a low-e coating has been added to double glazing, the next step to significantly reduce the U-value without substantially adding to the complexity of the window construction is to add a gas fill.

2. With air and argon, optimum U-values are reached at gap widths near 1/2 in. Even lower U-values can be reached, however, with gas fills of krypton (or perhaps mixes of krypton and/or other gases) at smaller gap widths.

3. Triple or quadruple glazings (with glass or plastic as the inner glazings) offer several options for the use of low-e coatings to produce windows with very low U-values.

4. Since the conductance values are added in series, adding each additional coatings and/or coated substrate provides diminishing returns (refer to Figure 4).

5. Moving a low-e coating across an air gap from its original position will not change the window's nighttime U-value, but will change its SC.

Future Technologies

Two promising window designs to reduce heat transfer while maintaining high solar transmittance are aerogel windows and evacuated windows. These technologies are in the research stage and their market introduction, if feasible, is probably years away. We mention them here to give the reader a glimpse of the future energy performance of windows. Both are logical technical extensions of current development trends.

An evacuated air space between glazing layers can eliminate conductive and convective losses between window panes (disregarding spacers). The window must also have a low-emittance coating to reduce radiative losses. Partially evacuated air spaces have been used in solar collectors to reduce thermal losses. Evacuated spaces in window systems pose new technical problems including the window's ability to withstand pressure differentials, safety concerns if the window should break, sealing the evacuated space, and economical production procedures. Research efforts in Europe and the U.S. (Benson et al. 1984) are directed at these problems. For structural and thermal reasons, air spaces generally must be smaller than 1/2 in (13 mm), and airspace pressures must be less than 10^{-5} atm. Current research has focused on window systems having small interpane spacing, 0.02 – 0.2 in (0.5 mm – 5.0 mm), at very low pressures (10^{-7} atm). At this pressure, the sealing technology becomes a critical factor and getters are required to trap gases (helium) that diffuse through the glass surfaces. Heat transfer through spacers and edges must also be considered. With an emittance of 0.05 on the #2 surface and a hard vacuum, an evacuated window can theoretically achieve an R8 insulating value (Benson et al. 1984).

Another promising means of reducing conductive and convective heat transfer in a double-glazed window is to fill the cavity with a transparent insulating material. Unfortunately, common insulating materials are either opaque to visible light or are transparent but scatter light and distort exterior views. However, silica aerogel, currently under development for use in windows, does not have these limitations. Because the silica particles comprising the microporous material are much smaller than wavelengths of visible light, aerogel is highly transparent. Due to slight scattering effects, current aerogel samples appear slightly yellow against a bright background or show a blue haze against a dark background (Rubin and Lampert 1983). Ongoing research is aimed at further reducing scattering and increasing transmittance. With approximately 95% of the air by volume in aerogel contained in pores smaller than the mean free path of air molecules, the thermal conductivity of aerogel will be lower than that of air. Measurements of aerogel's effective thermal conductivity (1.1×10^{-2} Btu/h/ft/F or 2.0×10^{-2} W/m $^{\circ}$C) confirm this (Rubin and Lampert 1983). Replacing the air in aerogel with CCL_2F_2 further reduces the thermal conductivity to between 0.8 and 0.9×10^{-2} Btu/h/ft/F (0.014 to 0.015×10^{-2} W/m$^{\circ}$C). An even greater reduction in thermal conductivity can be achieved at low pressures, where a conductivity of approximately 0.006×10^{-2} Btu/h/ft/F 0.010 W/m$^{\circ}$C) is obtained at pressures under 0.1 atm (Kistler 1935). While requiring essentially the same compressive strength as a window with a hard vacuum, the sealing technology for this "soft" vacuum should be simpler to achieve. Aerogel acts as its own transparent spacer with more than adequate compressive strength to balance air pressure. Since aerogel is opaque to most longwave infrared radiation, net radiative losses through aerogel will be on the order of those from double-glazed windows with low-emittance coatings. Recent research developments have produced aerogel samples using lower temperatures and pressures than previously possible, thus advancing the day when such a window-insulating material might be manufactured using low-cost, high-volume production techniques (Rubin and Lampert 1983; Tewari et al. 1985).

Figure 7 shows window U-value as a function of window thickness for double-glazed windows (with and without low-emittance coatings) and aerogel windows (air-filled and at low pressures). We see that these glazing units have a resistance value on the order of R8-R15. The commercial viability of these approaches and the incorporation of these

glazing elements into a practical window system will remain a challenge in the years ahead.

ANNUAL ENERGY FLOWS

Thermal performance of windows has generally been studied to determine peak thermal gains or losses and necessary equipment sizes. With recent interest in annual energy consumption attributable to fenestration systems, it is important to evaluate thermal performance in terms of seasonal and annual energy flows. Annual energy flows through buildings require making trade-offs between often opposing thermal and optical properties. To account for interactions between windows and other building components (i.e., solar gains or daylight vs. thermal loads), windows must be evaluated within the context of overall building energy performance. Reducing window heat transfer while maintaining relatively high solar transmittance can produce positive net window energy flows, even in winter in northern climates.

To illustrate this point, we use calculated U-values and shading coefficients for specific window systems in the building energy simulation model (DOE-2.1B) to calculate annual energy performance and cost results for a prototypical residence in Madison, Wisconsin. The number of heating degree-days in Madison is greater than in most U.S. climates except the northern Great Plains and parts of the Rocky Mountains. The 1512-ft^2 (143.1-m^2) one-zone, insulated, slab-on-grade, frame-construction house is described in detail, along with the simulation procedure and results, in an earlier report (Sullivan and Selkowitz 1985). To condense results of many hypothetical simulations, we examine window performance for many hypothetical combinations of U-value and SC. Although we calculated summer cooling energy requirements, we present here only the winter heating analysis. (Note that for an annual cost analysis in locations where electricity is expensive and fuel is cheap, a small cooling load may have a greater economic impact than a large heating load.) We plot lines of constant seasonal energy flux as a function of window parameters in Figure 8. This is the useful net energy provided to the house and properly accounts for night setback, unusable gains on mild days, etc.

We now consider the performance of several specific window systems. The U-values and shading coefficients of these windows are evaluated at ASHRAE winter design conditions. Unless otherwise specified, all glazing substrates are 1/8-in (3-mm), double-strength glass. In many cases, especially where low-emittance coatings are used, the U-value and/or SC for specific products may vary noticeably from the typical designs we present. These values represent heat transfer through only the glazed portions of windows.

Figure 8 shows a typical plot of net seasonal heating energy vs. U-value and shading coefficient for east-facing glazing in Madison. Lines of constant seasonal energy flow are superimposed on this graph for this window size, orientation, and location. Each window system with a given U and SC appears as a point on the plot. Plotting single glazing and various double- and triple-glazed systems shows that the best triple-glazed systems barely break even.

In Figures 9-11, generic highly insulating window systems are plotted as a function of U-value and SC on enlarged annual energy flow diagrams. East (similar to west), south, and north orientations are analyzed. We examined the following window systems.

1. Double, triple, and quadruple glazings with gaps ranging from 1/4 in (6 mm) to 1/2 in (13 mm). These systems are shown by solid lines in Figures 9-11. Heavy lines denote all glass glazing layers, while light lines mean that the inner layers are thin anti-reflective polyester films. The number of layers is shown in front of the line.

2. Double-pane windows with a gap width of 1/2 in (13 mm) having a low-emittance coating on the #3 surface. These window systems are shown by a dashed line in Figures 9-11, with the x´s corresponding to emittances of 0.4, 0.3, 0.2, 0.1, and 0.05.

3. Triple-pane windows having a low-emittance coating on surface #3. The case of a coating with emittance = 0.15 is shown by an x. In this case the middle glazing layer is a thin plastic film.

4. Gas-filled (argon) windows. These values are shown by black dots connected to their air-filled equivalents by a dotted line.

5. Evacuated windows. The three points (marked by an open box) assume low-emittance coatings on the #3 surface with e=0.2 (high SC, high U), e=0.1 (middle point), and e=0.05 (low SC, low U). Shading coefficients given here are for average coatings. The glazing layers are separated by 1/8-in-diameter solid glass spheres spaced every 2 in (Benson et al. 1984).

6. Aerogel windows. Because of uncertainty about some aerogel properties, the SCs and U-values of aerogel window systems in Figures 9-11 are shown by shaded rectangular vertical boxes. Air-filled aerogel is shown by a solid rectangular box, CCL_2F_2-filled aerogel by a cross-hatched box, and low-pressure air-filled aerogel by a clear box. For a given thickness (1 in or 25.4 mm), changing the air to CCL_2F_2 or to a soft vacuum will decrease the window's U-value while maintaining the same SC. We model an inch-thick aerogel window with these three fills. Alternatively, a thinner unit can be produced by keeping the same U-value and changing the fill.

These results assume a specific primary window area of 66 ft^2 (6.13 m^2). If the primary window-to-floor-area ratio is decreased (or increased), the role of SC in producing positive energy flows increases (or decreases). However, these results are not always linear with window size. As window size increases, benefits per unit area diminish as a greater fraction of solar gain ultimately becomes unusable. Results also vary for different building types and locations. In addition, where cooling loads are dominant and if the fenestration is unmanaged or poorly managed, high shading coefficients may be an overall energy liability; furthermore, different window system selections would be desirable in cooling-dominated climates.

CONCLUSIONS

Through the use of the computer model WINDOW 1.0, we were able to parametrically study the effects of environmental factors and window parameters on window U-values and shading coefficients. In addition we presented designs for highly insulating window systems using both commercially available technologies and technologies currently under research and development. Our general conclusions are:

1. For single glazing, U-values for annual energy calculations will often differ substantially from those derived for peak or design conditions. For double- and triple-glazed systems, the variation of U-value with T_o is usually small with respect to other uncertainties (i.e., glass deflections, frame-edge effects).

2. Wind speeds and temperature differences will have a noticeable effect on a single-glazed (with or without a low-e coating) window's U-value and shading coefficient. This effect becomes less pronounced with increased glazing layers, low-e coatings, or other window components that add to a window's insulating value.

3. The effects of incident solar radiation on a window's U-value can be quite large, depending primarily on glazing absorption but also on other window parameters and environmental conditions.

4. With the exception of heat-absorbing glazing, shading coefficients are not strongly dependent on outside temperature, wind speed, incident solar radiation, gap width, or gas fill.

5. A low-e window's shading coefficient is a strong function of coating transmittance, absorptance, emittance, and placement.

6. Low-e coatings will greatly reduce the radiative loss component in a window. A highly insulating window should also reduce conductive and convective losses. This can best be achieved through the addition of more glazing layers, gas filling, or both. Gas-filled low-e double- and triple-glazed windows can be produced using commercially available technologies. Gas fills offer lower heat-transfer coefficients at smaller gap widths and with the use of typical low-e coatings (e=0.15), can result in R3-R7 windows. A quadruple-glazed window with a gas fill can provide R8-R9 values. Note that in these triple- and quadruple-glazed systems, thin-film plastics can be used as the inner glazing layers, making them more economical and less bulky.

7. Evacuated and aerogel windows, still under research and development, offer the potential of R8-R15 windows in the years to come.

8. It is well known that conventional south-facing windows in energy-efficient residences can provide net energy benefits even in a northern climate. If double- or triple-glazed systems using low-e coatings and/or gas fills are used, these benefits can be extended to east and west glazings. Using aerogel or evacuated windows can provide greater savings to east, west, and south windows and even turn north windows into energy producers in the future. A similar analysis (Barakat 1985) for Canadian climates confirms this.

With the number of possible window designs increasing based on the use of new materials and the complexity of analysis increasing due to interests in annual energy performance, not just peak performance of windows, it is important that we properly account for both the window design and environmental parameters affecting window heat transfer. Some of the data and conclusions presented in this paper have already been incorporated into Chapter 27 ("Fenestration") of the ASHRAE Handbook-1985 Fundamentals. We suggest that, as part of a major revision intended for the 1989 Handbook, additional data on window system performance be added.

We emphasize that the U-values presented in this paper are for the glazed areas of windows only. In highly insulating window systems, frame and sash conductance and window infiltration become increasingly important. This subject has not been well addressed in the past; we hope future work will address this problem. The values presented in this paper are based on the use of specific convective correlations and glazing transmittance, absorptance, and reflectance properties. Other assumptions will result in slightly different U-values and shading coefficients. However, the general trends and conclusions should be the same.

We have used the calculational procedure presented here to determine U-values and shading coefficients since 1980 and have performed limited experimental verification based on hot-box measurements (Rubin 1982). We are now working to complete further validation studies of this analytical model. Related field measurement of window heat-transfer properties is reported in a companion paper (Klems 1985). Readers with interest in the WINDOW heat transfer model are encouraged to contact the authors.

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ACKNOWLEDGMENTS

Figure 10: Net annual useful energy flux in kBtu/yr-ft^2 of window area (1 kBtu/yr-ft^2 = 11.4 MJ/yr-m^2) through 66 ft^2 (6.1 m^2) of north-facing double- and triple-glazed and highly insulating window systems in a prototypical house in Madison, WI, expressed as a function of window U-value.
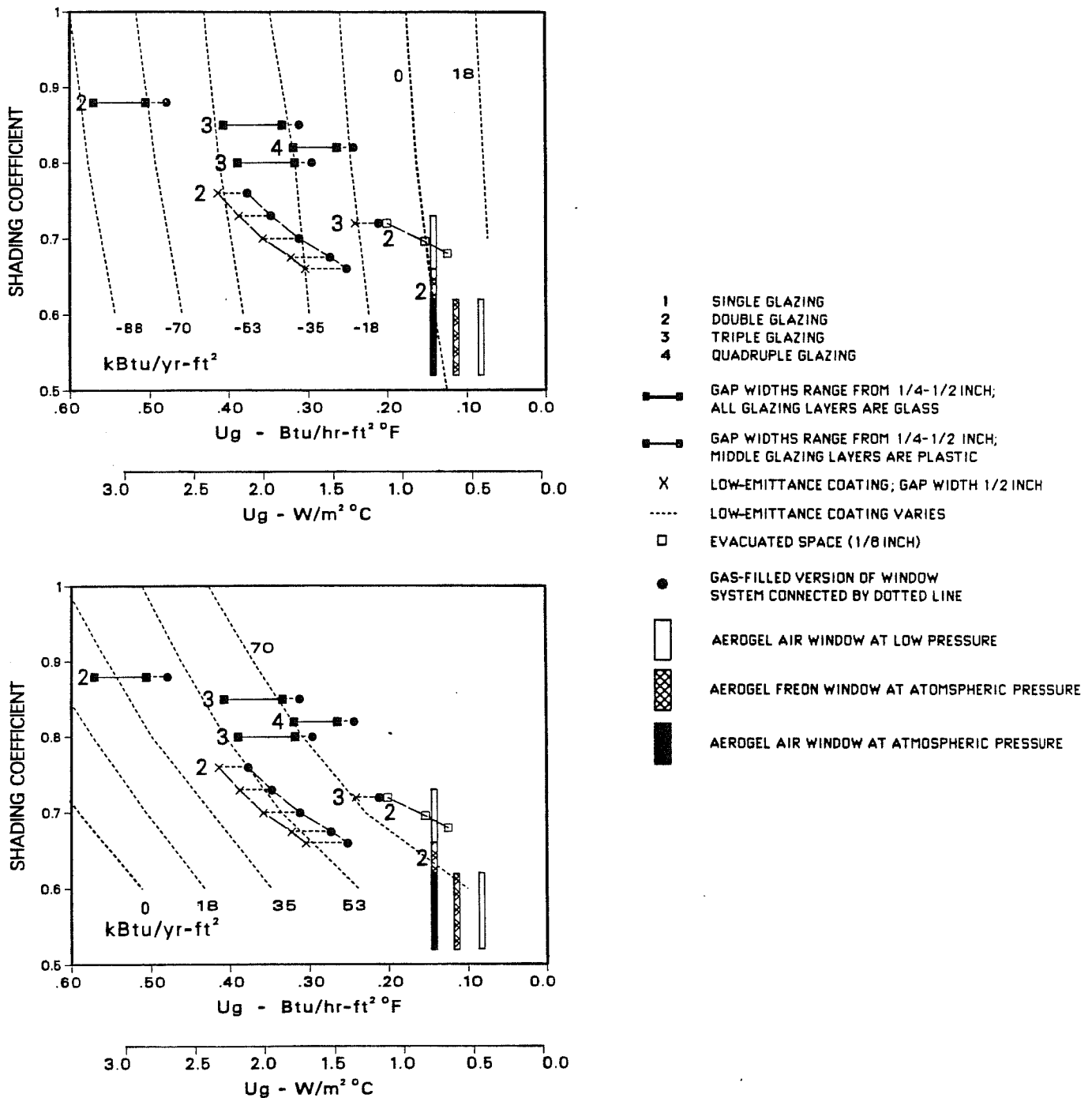

Top chart axes:
SHADING COEFFICIENT (vertical)
kBtu/yr-ft^2
Ug - Btu/hr-ft^2 °F
Ug - W/m^2 °C

Legend:

1	SINGLE GLAZING
2	DOUBLE GLAZING
3	TRIPLE GLAZING
4	QUADRUPLE GLAZING

GAP WIDTHS RANGE FROM 1/4-1/2 INCH; ALL GLAZING LAYERS ARE GLASS

GAP WIDTHS RANGE FROM 1/4-1/2 INCH; MIDDLE GLAZING LAYERS ARE PLASTIC

X — LOW-EMITTANCE COATING; GAP WIDTH 1/2 INCH

----- LOW-EMITTANCE COATING VARIES

□ EVACUATED SPACE (1/8 INCH)

● GAS-FILLED VERSION OF WINDOW SYSTEM CONNECTED BY DOTTED LINE

AEROGEL AIR WINDOW AT LOW PRESSURE

AEROGEL FREON WINDOW AT ATOMSPHERIC PRESSURE

AEROGEL AIR WINDOW AT ATMOSPHERIC PRESSURE

Bottom chart axes:
SHADING COEFFICIENT (vertical)
kBtu/yr-ft^2
Ug - Btu/hr-ft^2 °F
Ug - W/m^2 °C

Figure 11: Net annual useful energy flux in kBtu/yr-ft^2 of window area (1 kBtu/yr-ft^2 = 11.4 MJ/yr-m^2) through 66 ft^2 (6.1 m^2) of south-facing double- and triple-glazed and highly insulating window systems in a prototypical house in Madison, WI, expressed as a function of window U-value.

Figure 8: Net annual useful energy flux in kBtu/yr-ft^2 of window area (1 kBtu/yr-ft^2 = 11.4 MJ/yr-m^2) through 66 ft^2 (6.1 m^2) of east-facing single-, double-, and triple-glazed windows in a prototypical house in Madison, WI, expressed as a function of window U-value. The heat flux of an R-19 wall is shown as a reference.
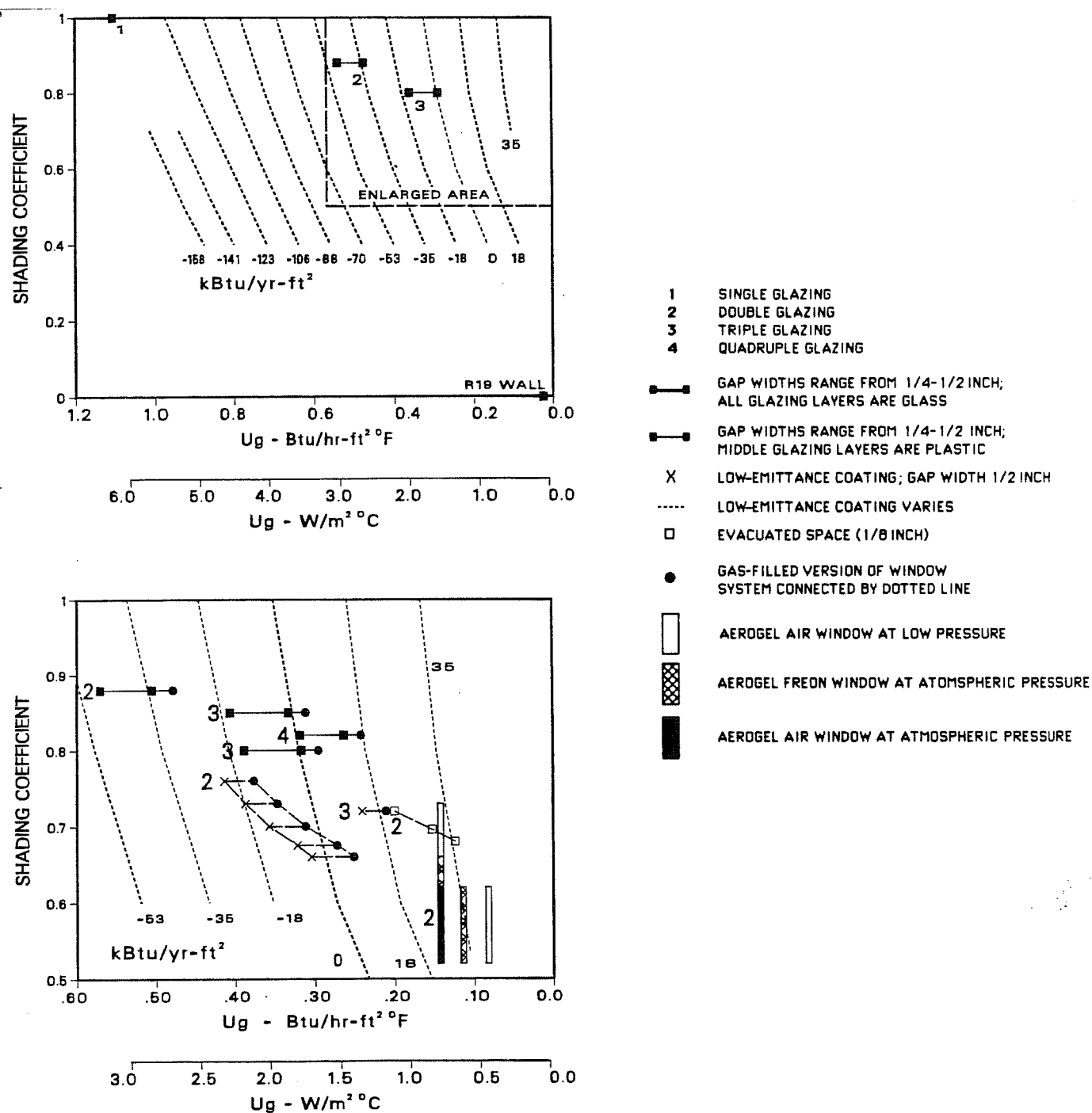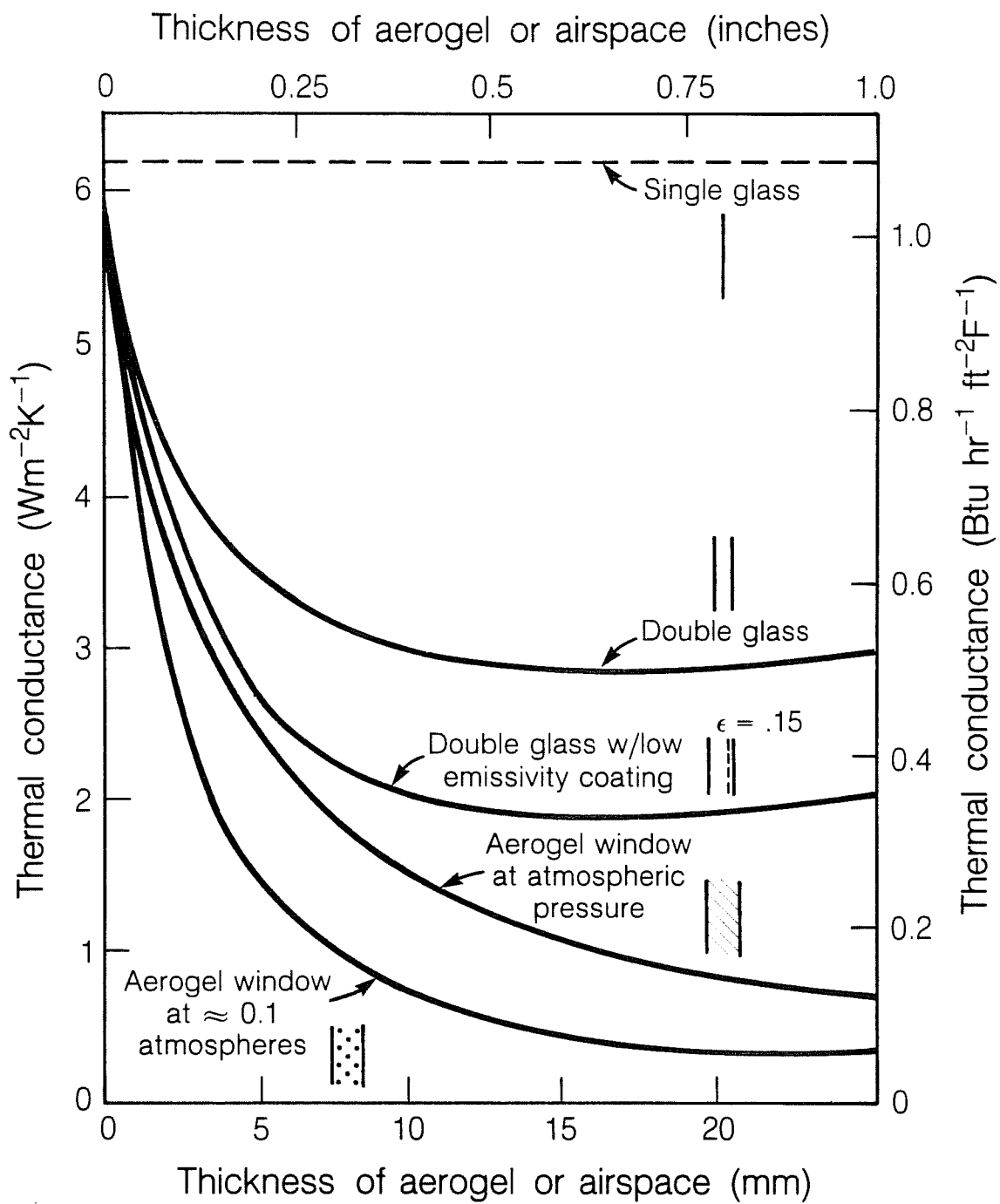

Figure 9: Net annual useful energy flux in kBtu/yr-ft^2 of window area (1 kBtu/yr-ft^2 = 11.4 MJ/yr-m^2) through 66 ft^2 (6.1 m^2) of east-facing double- and triple-glazed and highly insulating window systems in a prototypical house in Madison, WI, expressed as a function of window U-value.

Figure 7:   U-values of double-glazed and aerogel windows.
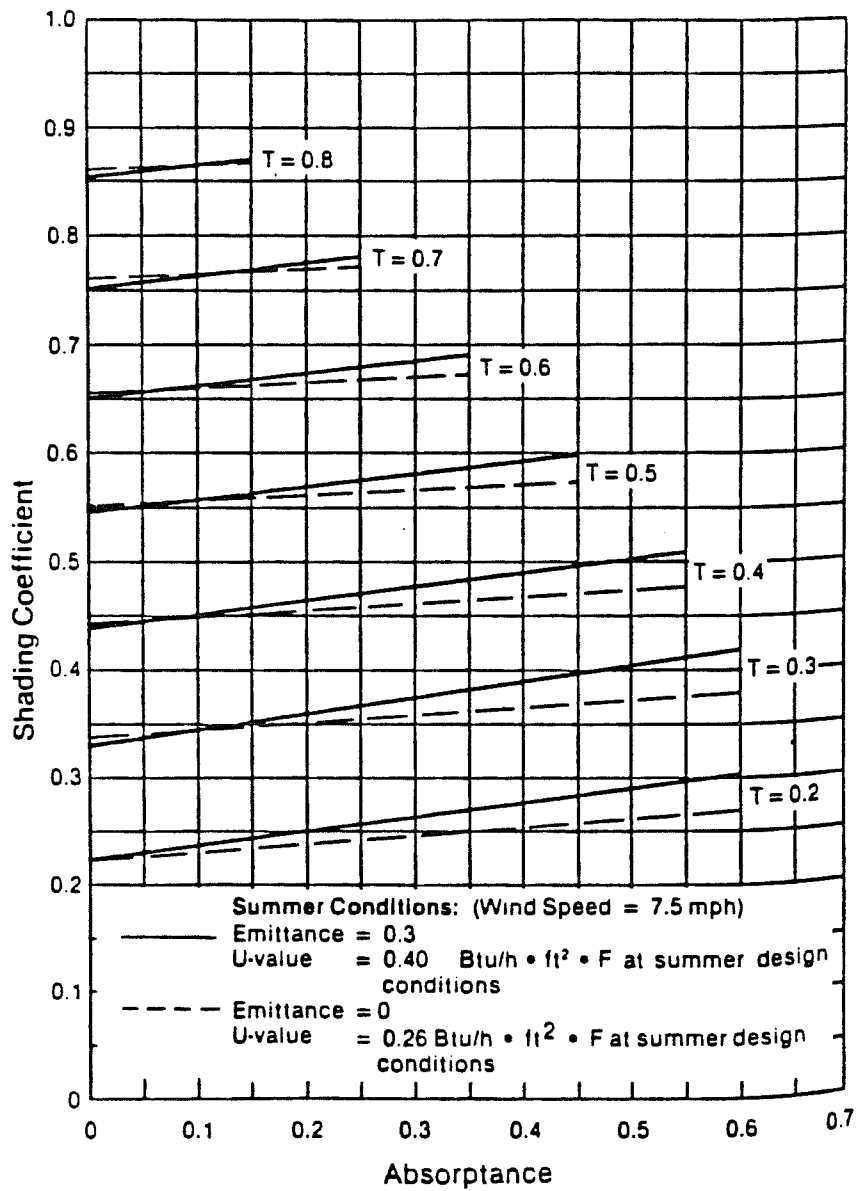
Figure 6: Shading coefficient as a function of absorptance, transmittance, and emittance: double glazing with low-emissivity coating on surface #2. (Figure reprinted from ASHRAE Handbook — 1985 Fundamentals, p. 27.31, by permission of ASHRAE.)
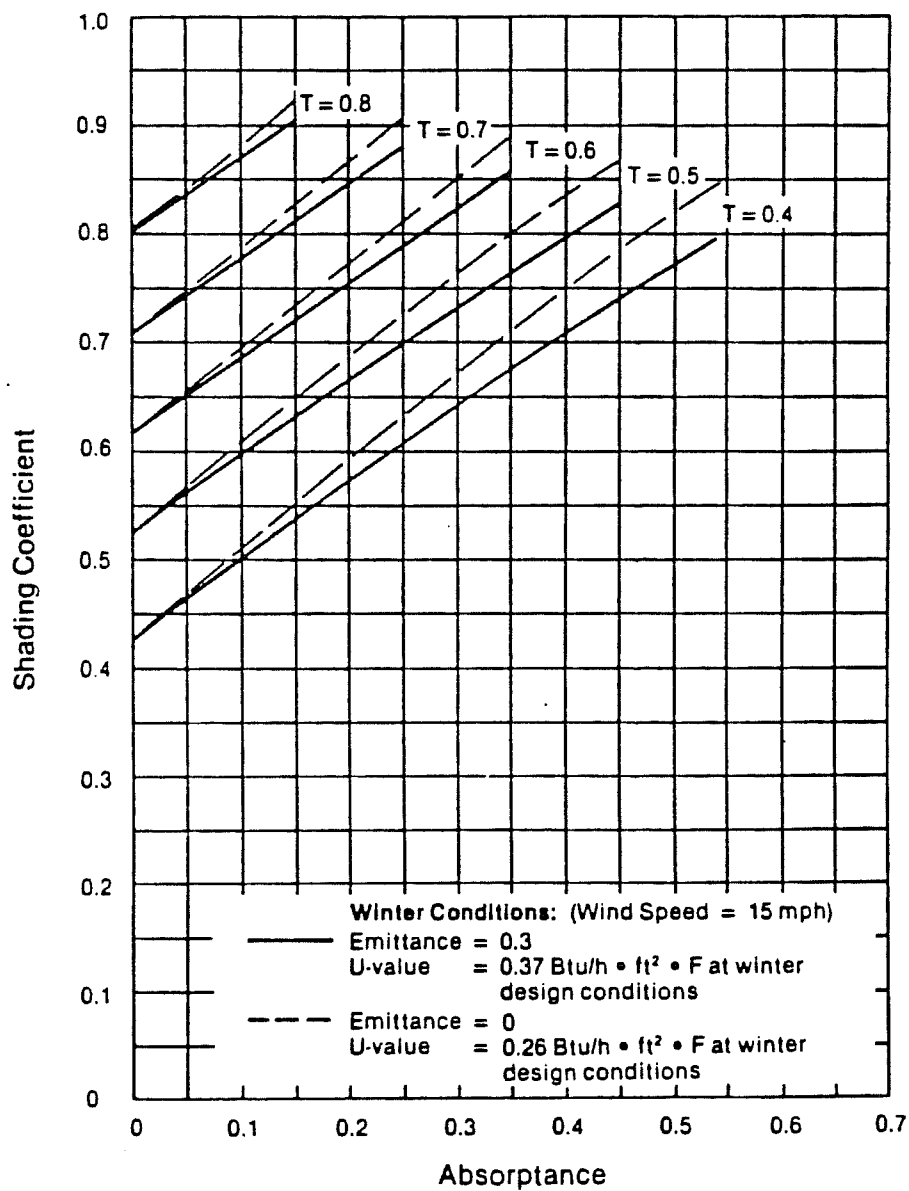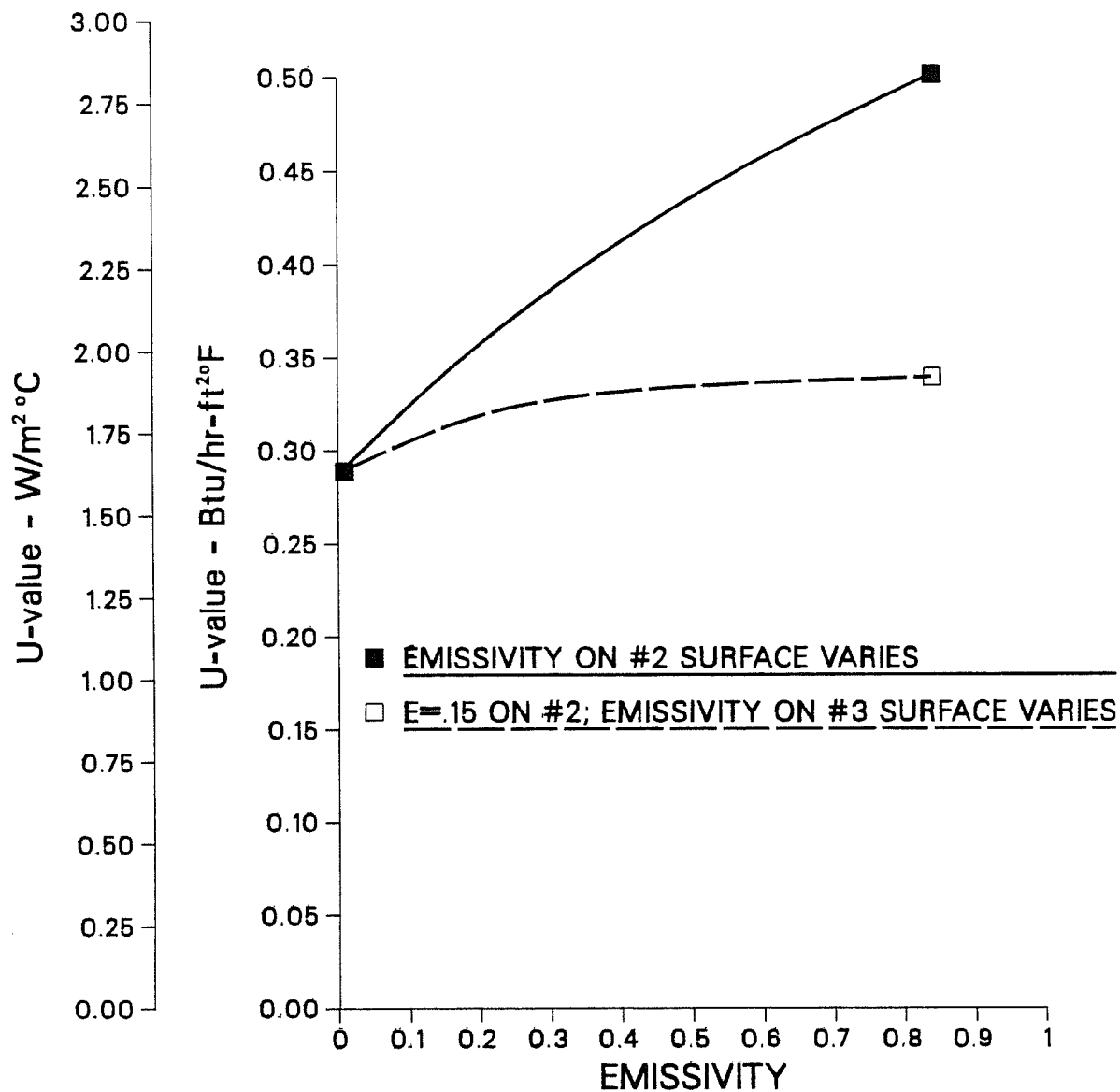
Figure 5: Shading coefficient as a function of absorptance, transmittance (T), and emittance: double glazing with low-emissivity coating on surface #3. (Figure reprinted from ASHRAE Handbook — 1985 Fundamentals, p. 27.30, by permission of ASHRAE.)

Figure 4: U-values of double-glazed windows: (1) varying the emittance of the #2 (or #3) surface; and (2) with a low-E coating on the #2 surface (E = 0.15) and varying the emittance of the #3 surface. ASHRAE winter design conditions and a 1/2-in (1.27-cm) gap are assumed.
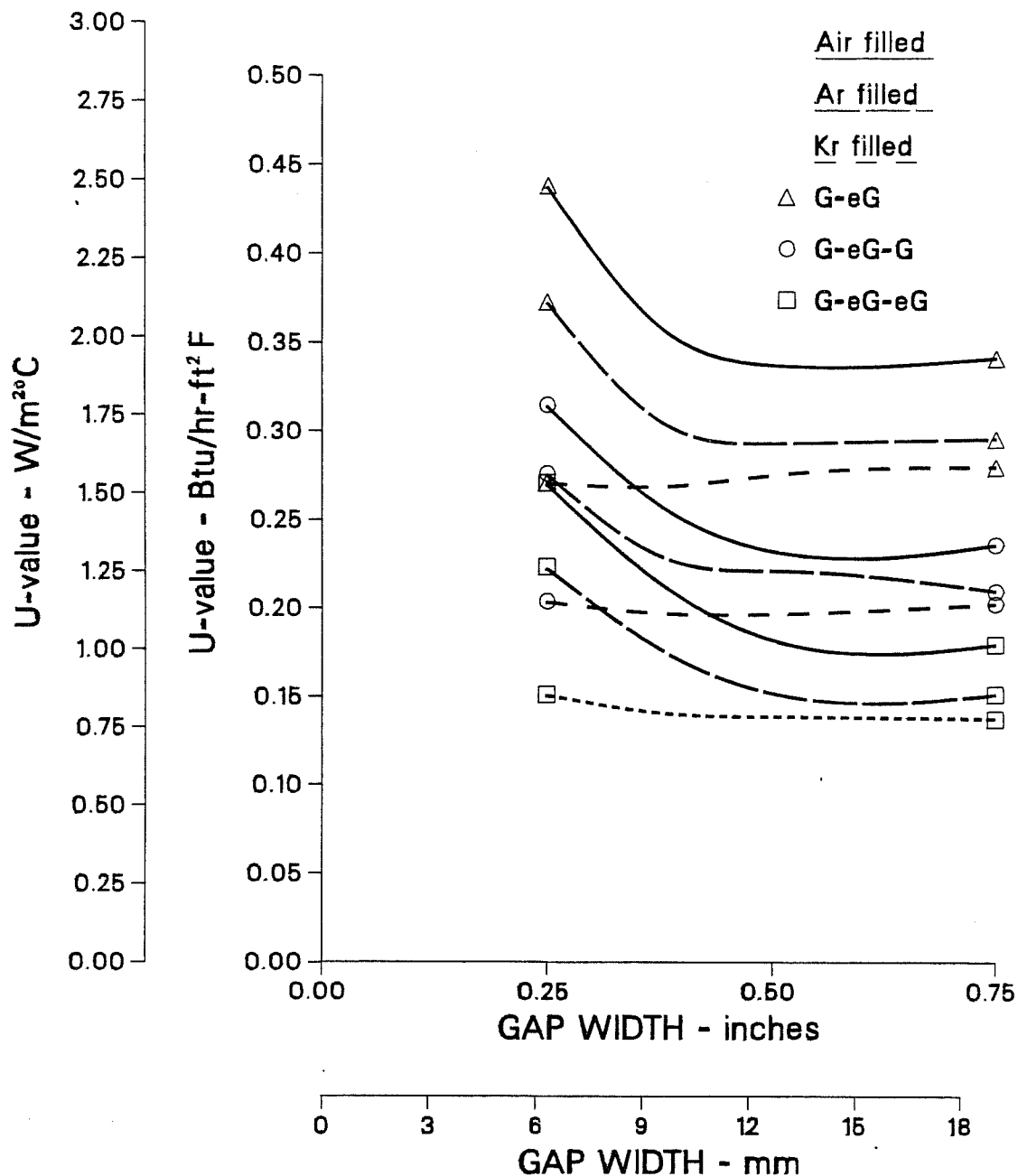
Figure 3: Window U-values as a function of gap width for windows with low-E coatings with and without gas fills. G-eG is double glazing with an E = 0.15 coating on surface #3. G-eG-G is triple-glazing with an E = 0.15 coating on surface #3; middle glazing can be a polyester film. G-eG-eG is triple glazing with an E = 0.15 coating on surfaces #3 and #5; middle layer can be a polyester film. All glazings' IR transmittances are assumed to be 0.
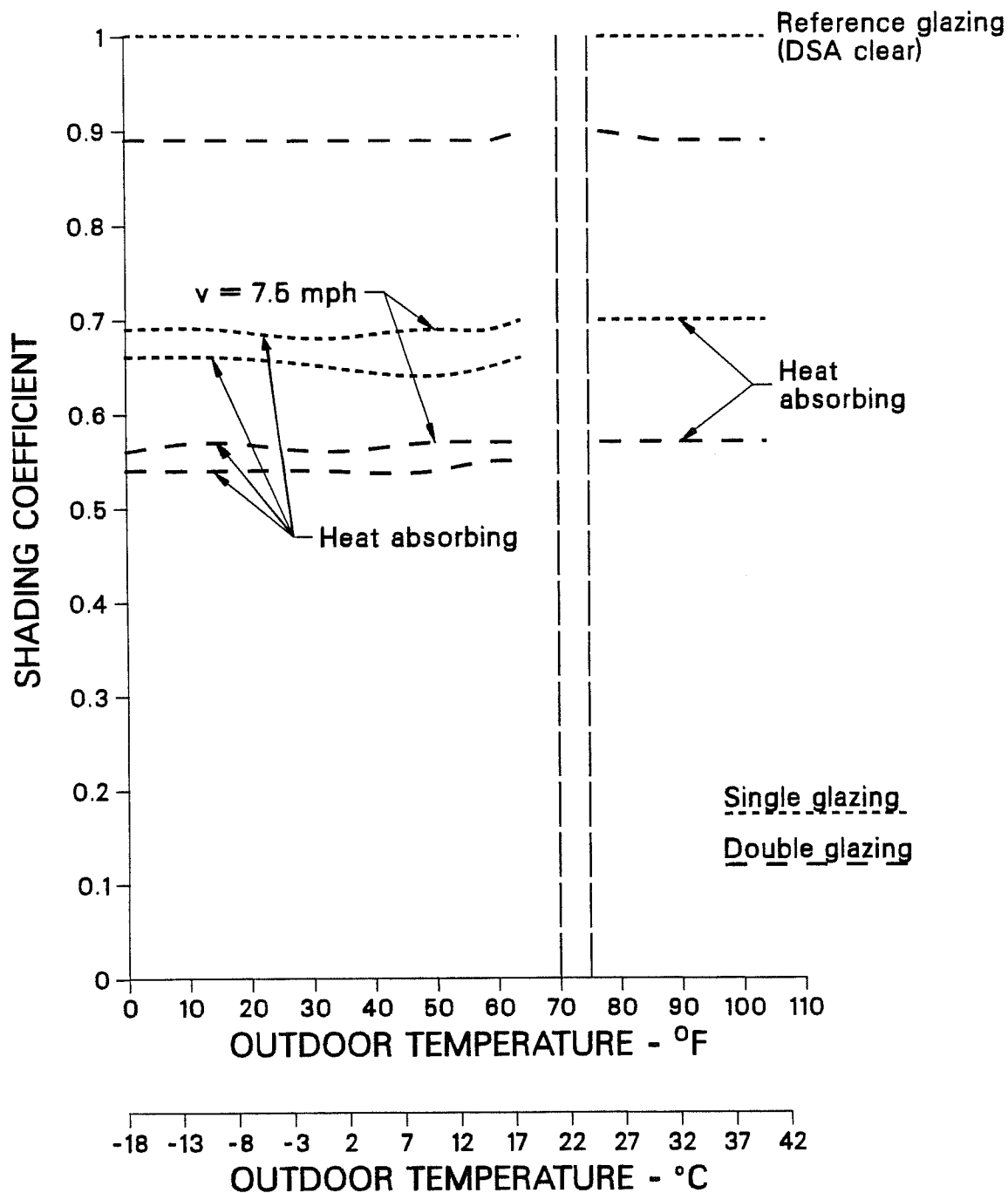
Figure 2: Window Shading Coefficients as a function of T_o, v and glazing type, (ASHRAE v, T_i design conditions unless otherwise noted). V is given in units of mph (1 mph = 0.447 m/sec). Glazing is clear (DSA) unless marked HA (heat absorbing). Double-glazing gap width is 1/2" (or 1.27 cm).
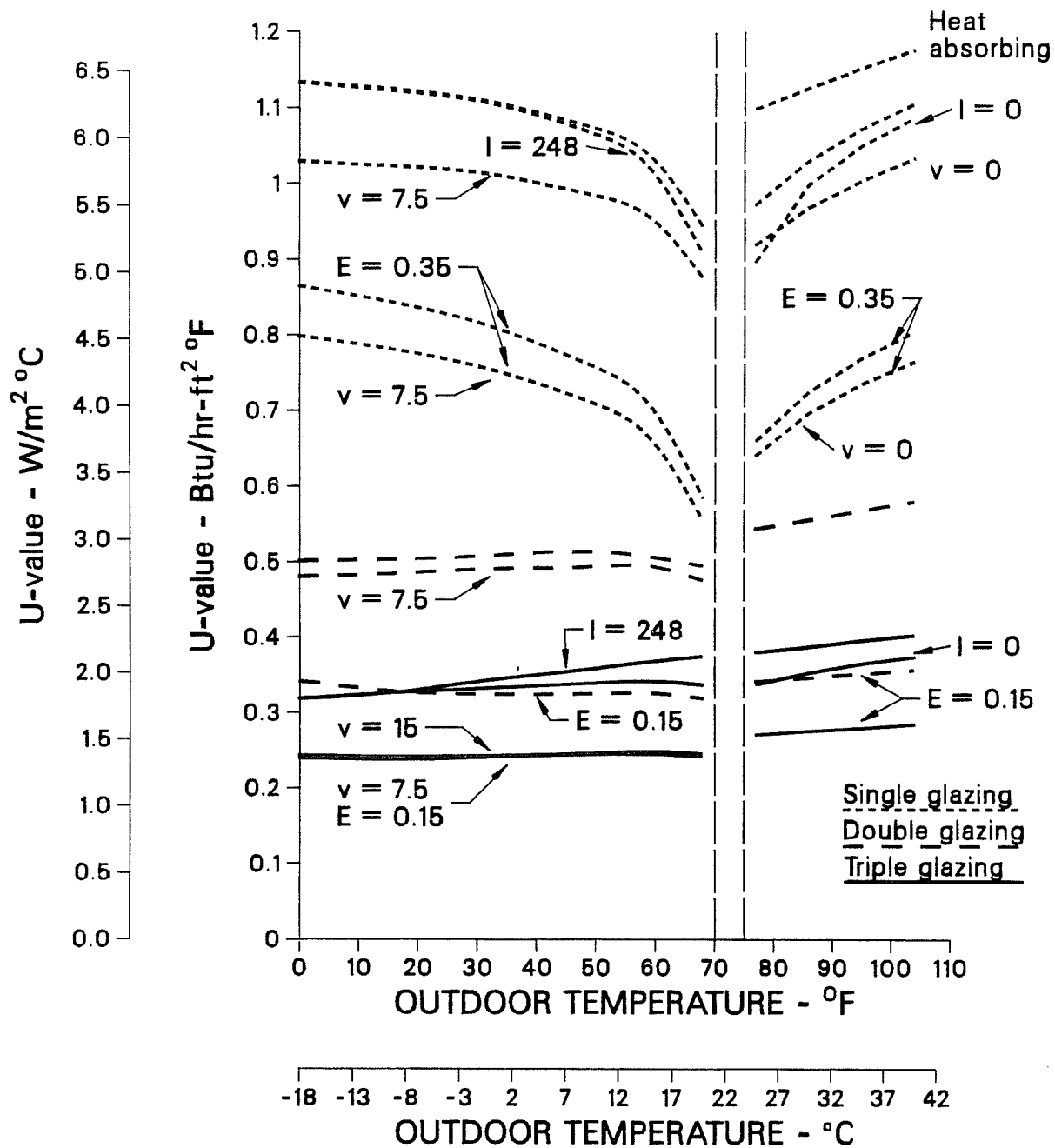
Figure 1: Window U-values as a function of T_o, v and I for single-, double-, and triple-glazed windows (gap widths are 1/2" or 1.27 cm) with and without low-E coatings. I is given in units of Btu/hr-ft²-F and v in mph. Note that 1 Btu/hr-ft²-F = 3.155 W/m² and 1 mph = 0.447 m/sec. Unless otherwise noted, environmental conditions are ASHRAE conditions, surface emissivity is 0.84, and glazing is clear (DSA). For glazings with low-E coatings, a = 0.1. Heat-absorbing units are denoted by HA.

Table 1: U-Values of Highly Insulating Windows at Standard Winter Design Conditions in Btu/hr-ft^2-F (W/m^2 —K)

Window Design*	Gas Fill	Gap Width $\frac{1}{4}"$ (6.4 mm)		Gap Width $\frac{1}{2}"$ (12.7 mm)	
Double Glazing G—G	Air	0.58	(3.27)	0.50	(2.85)
	Ar	0.52	(2.97)	0.47	(2.66)
	Kr	0.46	(2.63)	0.46	(2.62)
GE$_h$ —E$_h$G e = 0.35	Air	0.47	(2.66)	0.36	(2.06)
	Ar	0.39	(2.21)	0.31	(1.77)
	Kr	0.30	(1.69)	0.30	(1.71)
G—E$_s$G e = 0.15	Air	0.45	(2.56)	0.34	(1.94)
	Ar	0.37	(2.09)	0.29	(1.62)
	Kr	0.27	(1.53)	0.27	(1.56)
G—E$_s$GE$_h$ e = 0.15 e = 0.35	Air	0.39	(2.21)	0.30	(1.70)
	Ar	0.32	(1.83)	0.25	(1.44)
	Kr	0.24	(1.37)	0.24	(1.39)
G—E$_s$G—G e = 0.15	Air	0.33	(1.88)	0.24	(1.38)
	Ar	0.27	(1.54)	0.21	(1.17)
	Kr	0.20	(1.15)	0.20	(1.11)
G—E$_s$G—E$_s$G e = 0.15	Air	0.29	(1.62)	0.19	(1.07)
	Ar	0.22	(1.26)	0.15	(0.85)
	Kr	0.15	(0.86)	0.14	(0.79)
G—E$_s$G—E$_s$G—G e = 0.15	Air	0.23	(1.32)	0.15	(0.88)
	Ar	0.18	(1.04)	0.13	(0.72)
	Kr	0.13	(0.73)	0.11	(0.65)

*G denotes a glazing layer; E$_h$, a low-E "hard" coat (e = .35), or E$_s$, a low-E "soft" coat (e = .15), on one side of the glazing. IR transmittance of all glazing layers are taken to be 0.